Max Planck, the Man and His Work[1]

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WHENEVER I THINK OF MAX PLANCK, my venerated teacher, with whom I took my doctorate in theoretical physics and with whom I was connected for thirty years in Berlin, I have an exalted and solemn feeling. I think of him, as the whole world of physicists does, as the creator of the world-shaking quantum theory; but for me he is even more—all that is one with truth, and hence with justice. He was never swayed by the opinion of others, not only in science but also in human relations, because he followed the path which he thought was the only true and good one. And this he did, not intolerantly, but in his own most modest manner. Never did he wish to appear more than he was. And this enhanced his commanding and gracious personality.

Planck's manner was determined to a certain extent by his education and the circle in which he grew up. He came from a family of jurists. He was born April 23, 1858, in Kiel, the sixth child of Wilhelm Planck, professor of law, and of his wife Emma (nee Patzig.) In his ninth year he moved to Munich, where his father had been offered a professorship at the university. The physicist Planck inherited the correct juridical way of his family in the administration of any position; for instance, as permanent secretary of the Prussian Academy of Science, he insisted upon the strictest objectivity and exact adherence to rules or decisions. He directed meetings in correct parliamentary manner, and always in his own charming and gracious way.

For a correct picture of Planck's personality, one must consider his training and his work. In Munich, Planck was a pupil in the famous Maximilian Gymnasium where, at the age of seventeen, he passed the university entrance examination. At first he was uncertain whether to select classical philology, music, or physics, but he finally decided on physics, in spite of the fact that Jolly, then professor of physics at the University of Munich, advised him against it, since in the field of physics there was nothing new to be discovered. Music remained for him a source of delight and recreation for the rest of his life.

Planck's decision to study physics may be attributed primarily to his mathematics teacher at the gymnasium, Herman Mueller, to whom he owed much, and through whom he became acquainted with the principle of the conservation of energy, which later became the subject of a prize essay for the Goettingen Academy. Planck studied in Munich from 1875 till 1877. There he was far more attracted by the mathematician Bauer than by the physicist Jolly. It was Bauer who stimulated Planck's enthusiasm for higher mathematics and its unique methods of reasoning.

From 1877 to 1879, Planck continued his studies in Berlin. There his scientific horizon was considerably broadened by attending the lectures of Helmholtz, Kirchhoff, and Weierstrass; and the pioneering work of these research men was readily accessible to him. However, the lectures of Helmholtz were not, as Planck wrote later, of any particular advantage to him. With the exception of three (including Planck) the students finally stayed away. In Planck's words, "We had the feeling that in these lectures, Helmholtz was at least as bored as we were." Here was another example of a genius who is not necessarily a good teacher! Planck had similar experiences with Kirchhoff. "His lectures," says Planck, "gave the impression of being learned by heart; they were dry and monotonous. Nobody dared to doubt anything. As a consequence we did not learn very much, because one only learns by asking questions." Under these circumstances Planck was able to fulfill his desire for scientific knowledge only by reading on subjects of interest to him, and these happened to be subjects connected with the energy principle. He found the papers of Rudolph Clausius, written in lucid, understandable language. He said later that their illuminating clarity impressed him so tremendously that he became enthusiastically absorbed in their serious study.

Planck particularly appreciated Clausius' precise formulation of the two laws of thermodynamics and the clear distinction between the two. Up to then, as a consequence of the theory of heat as a substance, it was assumed that the transition of heat from a higher to a lower temperature was similar to the falling of a weight from a higher to a lower position. This erroneous idea was not to be displaced easily. Clausius, on the other hand, according to Planck, derived his proof of the second law from the hypothesis that "heat cannot pass spontaneously from a colder to a warmer body." This hypothesis, however, requires clarification. It not only expresses the idea that heat does not go directly from a colder to a warmer material, but also indicates that in no way is it possible to transmit heat from a colder to a warmer material without "some other change remaining in nature as a compensation." While trying to clarify this point,

[1] Translated from the German by members of the Department of Physics, Purdue University. Based in part on Max Planck's *Wissenschaftliche Selbstbiographie*, Leipzig: Johann Ambrosius Barth (1948); English trans., New York: Philosophical Library (1949). See also MEISSNER, W. *Ber. Bayer. Akad. Wiss.*, 1 (1948).

Planck found a formulation of the hypothesis that seemed simpler and more convenient: namely, the process of heat conduction cannot be completely reversed by any means; or, the expansion of a gas without the performance of work cannot in any fashion be made completely reversible—a concept that is the same as that of Clausius, yet not requiring a special explanation. Planck calls a process "natural" which cannot be made reversible. Today we call it "irreversible." "To this very day," Planck wrote later, "I find, instead of the above definition of irreversibility, the following: 'A process is irreversible if it cannot take place in the opposite direction.' This definition is not sufficient. Because, at the outset, it is quite conceivable that a process that cannot take place in an opposite direction could become somehow completely reversed." In an irreversible process nature has a great "preference" for the final state. A measure of this "preference" is Clausius' entropy. The meaning of the second law of thermodynamics is, then, an increase in the sum of the entropies of all bodies participating in the process.

Planck finished his doctor's thesis in 1879 without the assistance of his teachers. He presented it after his return to Munich and received his degree in the same year. Very much to his disappointment Planck found that his thesis had made no impression whatsoever on the contemporary world of physics. His Munich professors just let it pass. Adolf von Bayer, the famous chemist, let it be understood that he thought theoretical physics superfluous. Helmholtz very likely never read the paper. Kirchhoff definitely disapproved, with the remark that the concept of entropy, which is only measurable through a reversible process and hence can only be thus defined, cannot be applied to irreversible processes. It was impossible to approach Clausius, who did not answer letters; nor did an attempt to introduce himself personally in Bonn have any result, because Clausius was not at home. Correspondence with Carl Neumann, in Leipzig, had no result whatever.

Planck had a similar experience in Munich (1880) with his habilitation paper, "States of Equilibria of Isotropic Bodies." He made use of the general results of his Ph.D. thesis for the solution of a number of concrete thermodynamic (particularly physicochemical) processes, but this work likewise made no impression on the physicists of his day.

These rather disheartening experiences did not prevent Planck, convinced of the importance of the task at hand, from continuing the study of entropy. It is characteristic of his sure intuition and superior scientific insight, as well as of his happy disposition, that lack of recognition did not discourage him; far from it, he continued in the direction in which he had started, and this enabled him to develop the quantum theory, his greatest achievement. The next problem that Planck attacked was the thermodynamic equilibrium of gaseous mixtures, whereby he made use, for the first time, of Helmholtz' "free energy."

Stimulated by the desire "to become somehow favorably known in the scientific world" and to receive a professorship, Planck decided to work on the prize problem set by the Goettingen philosophical faculty for the year 1887 concerning the nature of energy. It is true, he received only second prize—undoubtedly because, in a controversy between Wilhelm Weber, professor of physics in Goettingen, and Helmholtz, Planck with his usual sincerity definitely took Helmholtz' side. In judging the paper the faculty disagreed with his remarks. Even now it is a pleasure to read his clear and comprehensive treatise, in which the results of Mayer, Joule, and Helmholtz are discussed in detail, and in which Planck gave some ideas of his own.

Before this work was finished, Planck received a call as professor extraordinary of theoretical physics at the University of Kiel (spring of 1885). "This offer," so Planck writes, "came to me as a redemption. I consider one of the happiest occasions of my life the moment when Ministerial Director Althoff . . . informed me about the conditions of my appointment."

During this stay in Kiel, from 1885 to 1889, Planck again worked on his favorite theme and wrote a number of essays under the title "The Principle of the Increase of Entropy." In these articles he dealt with heterogeneous equilibria (the equilibria between various states of aggregation), the mass law of action for gases, and the derivation of the thermodynamic functions for dilute solutions (particularly the entropy). His results went far beyond those of Van's Hoff. The activity coefficient, which enters into Van't Hoff's treatment of the boiling point elevation, must have the value 1, as Planck showed from the second law of thermodynamics. A deviation from the value 1 would be possible only if the dissolved molecules were dissociated. In 1943, in his paper on the history of the discovery of the elementary quantum of action, he states that some of his results, in their fruitful applications, were anticipated by the great American physicist J. W. Gibbs; nevertheless, one must admit that certain results of Planck's were truly pioneering.

It is also important to note that, even then, Planck was sure of himself as regards the objections of others. Particularly with respect to the remarks of the Swedish physical chemist Svante Arrhenius, he was able to defend himself and to prove clearly that the use of ideal processes is permissible. In this connection he also points to the use of ideal semipermeable membranes by Gibbs and Van't Hoff:

> In view of this undoubted success, one must admit that these ideal processes are a most useful research tool, and one must expect that, if properly used, they will in the future lead to new results. Indeed, I would say that they are a particular triumph of the human mind, which, with their help, has been able to discover the correlation between laws of nature in fields that are entirely closed to direct experiments.

In the spring of 1889, after the death of Kirchhoff, Planck, at thirty, was called to the University of Berlin as his successor. Undoubtedly he had been recommended by Helmholtz, who had been particularly impressed by Planck's prize essay on the energy principle, who had appreciated his exceptional qualifications, and who had known him personally at an earlier time. In Berlin he had the great fortune to become intimate with Werner von Siemens, and particularly with Helmholtz. Of this we shall speak later.

In science Planck continued his thermodynamics work until 1896. After a few minor papers, he published the fourth part of his great work on the principle of the increase of entropy, which presented the theories of thermoelectricity and of the electrolytic concentration cell (1891). Clausius had worked from 1867 until his death editing his collected papers on the mechanical theory of heat, but was unable to finish. After Clausius' death in 1888, Planck and K. Pulfrich edited the third volume of Clausius' treatise, in which the kinetic theory of gases was discussed. This volume appeared in 1894. Planck also edited Volume III of Kirchhoff's lectures on electricity and magnetism (theoretical physics).

In 1892 Planck was promoted to full professor. In 1893 he published an outline of general thermochemistry. In the same year, in the Physical Society of Berlin, he delivered a memorial address on Heinrich Hertz, which was greatly appreciated by Helmholtz. In 1894, Planck was elected to the Prussian Academy of Science, in which he served from 1912–1938 as permanent secretary of the mathematical-physical science section.

Of his many shorter papers mention should be made of a publication on the proof of the Maxwell distribution law (1896) in the proceedings of the Bavarian Academy of Science. A remark on a demonstration of a new type of harmonium in the "true" natural scale (system of C. Eitz) appeared in the proceedings of the Physical Society of Berlin in 1893. Planck, with his outstanding musical talent, had a particular interest in this harmonium (as will be discussed later).

In 1897 the first edition of his lectures on thermodynamics appeared, to be followed later by the publication of some of his other lectures. His election to the Academy and his contacts in the Physical Society gave him the impetus to work on heat radiation and to develop his theory of radiation, which later won him the Nobel prize. What he had particularly in mind in this paper was the interrelation of electrodynamics with thermodynamics. He had come to the conclusion that in every physical process the behavior of entropy has to be considered, and that this must also hold for the theory of radiation. Again he used ideal processes, which he had already justified in detail in his thermodynamics.

Following Kirchhoff's radiation law, he considered an evacuated cavity, bounded by totally reflecting walls, in which are located linear electrical oscillators of definite characteristic frequency and with weak radiation damping. He believed that, through irreversible radiation processes, the black-body radiation, even assuming arbitrary starting conditions and applying Maxwell's theory, would lead to a stationary state—thermodynamic equilibrium. Boltzmann pointed out, however, that this approach is erroneous, hence a new principle had to be added to reach the final goal. This was the hypothesis of "natural radiation," according to which the various partial vibrations of the heat radiation waves are entirely incoherent. Only with this hypothesis can radiation processes be considered irreversible so that thermodynamic equilibrium is reached. On the basis of this irreversibility, Planck was able to find an expression for the entropy of the oscillator, as well as of the black-body radiation itself. In thermodynamic equilibrium this entropy has a maximum, and the corresponding final state depends only on the absolute temperature. The entropy is a function of energy and of frequency, the form of which (introduced by Planck) contains a certain arbitrariness. With this first assumption for the entropy Planck derived Wien's law (1896) for the energy distribution in black-body radiation. In any event, he recognized then that the dependence of entropy on the energy and the frequency has a fundamental importance for the investigation of heat radiation. His assumption for the value of the entropy had to be discarded when it was found that Wien's radiation law was not generally confirmed by measurements. O. Lummer, E. Pringsheim, and, later, F. Paschen pointed out deviations in the range of long wavelengths.

A decisive change was brought about when F. Kurlbaum presented the results of energy measurements for very long wavelengths (carried out with H. Rubens) in a session of the German Physical Society (October 19, 1900). These measurements indicate that, with increasing temperature, the intensity of the black-body radiation approaches proportionality to the absolute temperature T, corresponding to Rayleigh's radiation law (1900). This, however, contradicts Wien's radiation law, according to which the intensity of radiation must always remain finite. In view of these results, communicated to him a few days before the session of the Physical Society, Planck started looking for a way out of the difficulty, and found at first an empirical solution. According to Rayleigh's radiation law, since the energy U of the Planck oscillator at a fixed frequency is always proportional to the intensity of radiation (Rayleigh's radiation law) if T is the absolute temperature, $U = CT$. With the thermodynamic relation for the entropy at constant volume, $\frac{dS}{dU} = \frac{1}{T}$, one has $\frac{d^2S}{dU^2} = -\frac{C}{U^2}$.

To Planck's first assumption for the entropy and Wien's law corresponds the value: $d^2S/dU^2 = -1/a\nu U$, where ν is frequency per second. Planck now set up an interpolation formula for the two values of d^2S/dU^2, setting $d^2S/dU^2 = -1/(a\nu U + U^2/C)$. This interpolation formula, together with the expression for $dS/dU = 1/T$, leads immediately to the Planck radiation law: $I_\nu = U\nu^2/c^2 = C_1\nu^3/(e^{c_2/T} - 1)$, where c is the light velocity. He finished his calculations in time to communicate the results at the Physical Society session of October 1900. I myself have seen a postcard from Planck to Rubens communicating his radiation law even before this session. The law had already been confirmed by Kurlbaum and Rubens, and by Lummer and Pringsheim, and the agreement became even better with more precise measurements.

Within the next two weeks, Planck was able to derive the empirical interpolation formula from theory.[2] The salient point was to find an unambiguous way to calculate the dependence of entropy on energy and frequency. He realized that this was impossible by means of electrodynamics alone, so he used Boltzmann's method and set the entropy proportional to the logarithm of probability. Only through the introduction of energy quanta was he able, with the aid of probability calculations, to obtain his interpolation formula. The energy quantum was set equal to the product of the frequency and a new constant h—Planck's elementary quantum of action. From the experimental values of the radiation constants, he was able, not only to calculate the numerical value of the elementary quantum of action, but also to determine the proportionality factor k in the Boltzmann expression for entropy, as well as the value of e, the charge of the elementary quantum of electricity. The following values resulted:

$$k = 1.346 \times 10^{-16} \text{ erg}/^\circ K; \; h = 6.55 \times 10^{-27} \text{ erg-sec}; \; e = 4.69 \times 10^{-10} \text{ esu.}$$

Planck's radiation law then took the form $I\nu = U\nu^2/c^2 = h\nu^3/c^2(e^{h\nu/kT} - 1)$, so that the constants C_1 and C_2 are now universally determined. Today the best values for the constants k, h, and e are the following: $k = 1.380_7 \times 10^{-16}$ erg/°K; $h = 6.626 \times 10^{-27}$ erg-sec; $e = 4.803 \times 10^{-10}$ esu. Planck's calculated values of 1900 were surprisingly good! The constant k, which Boltzmann had never really used, was calculated by Planck for the first time (as Planck has pointed out several times—e.g., in his Nobel prize address). It should really not be called Boltzmann's constant, but rather the Boltzmann-Planck constant. The calculation of the elementary quantum of electricity e from radiation measurements was not taken very seriously by many, in spite of the fact that in 1900 it was by far the most accurate determination. This was first demonstrated by the measurements of H. Geiger and E. Rutherford in 1908. As Rutherford said later, Planck's calculation made an overwhelming impression.

In his first derivation of the radiation law, Planck had assumed quantization of both emission through oscillators, as well as absorption through resonators. This is the presentation in Planck's lectures during the winter semester of 1905–06 on the theory of heat radiation (published in 1906). For some time Planck assumed, instead of absorption in quanta, a continuous absorption. But this derivation was not particularly satisfying. I still remember how Nernst, in the session of the Physical Society in Berlin, when Planck discussed this new derivation, at once contradicted it and spoke of something similar to Einstein's photons, so that Planck left the session somewhat depressed. At first, however, he persisted in this new derivation.

The reason for all the difficulties was quite profound. It is to be found in the dual nature of the quantum of radiation which behaves, depending on circumstances, sometimes like a particle and sometimes like a wave. It is known that Einstein first introduced with striking success the hypothesis that not only emission takes place in quanta, but that also heat and light rays are propagated as quanta—photons. But already Einstein's derivation of Planck's law, considering photons in a cavity, involves the dual nature of the photons: the photons were ascribed a certain frequency. The dual nature of the photons is displayed particularly in the energy fluctuations of heat radiation (Einstein). They are composed of one term proportional to the quantum of energy, and an average energy (quantum term); but there is a second term that is proportional to the square of the average energy (classical interference term; Lorentz). Planck has also treated this fluctuation law of Einstein's in some detail.

He continued to discuss other questions in this field. In this connection, we particularly want to mention that, in a communication to the Franklin Institute in 1927, Planck, considering the development of the quantum theory through De Broglie, Heisenberg, Born, Jordan, Schroedinger, and others, says:

> The classical theory recognizes and treats only the two extreme cases; on the one side, corpuscular motions, on whose outermost border lies the uniform motion of a particle in a straight line; on the other side, wave-motions, on whose outer limit lies the static, homogenous field. Looked upon from the newly established point of view, there is neither pure corpuscular motion, nor any pure wave-motion. Rather, every corpuscular motion includes something of wave-motion, and every wave-motion something of corpuscular motion. The difference is only gradual and quantitative. In the motion of a particle, as soon as the ratio of the impulse to the curvature of the path, which in motion in a straight line has an infinite value, sinks to the order of magnitude of the universal constant of action, the laws of wave-motion begin to play an appreciable part. And *vice versa*, in monochromatic light, as soon as the ratio of its energy to its frequency, which is infinite in a static field, sinks to the order of magnitude just mentioned, the corpuscular laws begin to be appreciable. In what relation, however, the corpuscular laws stand to the laws of wave-motion in the general case, remains the great problem, to which at the present time a whole generation of investigators is devoting its best efforts (*J. Franklin Inst.*, **204**, 18 [1927]).

This synthesis Planck has attempted in papers appearing in the *Annalen der Physik* (1940, 1941). Some of his results had already been published in earlier papers by Kramers. The changed action function is new and also the change in the boundary conditions of wave mechanics.

[2] The theory was finally communicated to the Prussian Academy on December 14, 1900, in "The Birthday of the Quantum Theory" (Laue).

If one asks for the most logical derivation of Planck's radiation law available today, the one least open to objections, one could say the following: Quantum mechanics has shown that, for identical particles, only Bose-Einstein or Fermi-Dirac statistics can be used (the latter only if the Pauli principle has to be used). To derive the radiation law free from classical electrodynamics, which is incompatible with quantum theory, then, with Bose, one reasons as follows: (1) The radiation consists of light quanta of energy $h\nu$, and a momentum corresponding to the relativistic relation between energy and mass. (2) The phase volume (position coordinates and momenta) for light quanta consists of cells of magnitude h^3. (3) The definition of entropy as k times the logarithm of the thermodynamic probability, and Bose-Einstein statistics applied to radiation in thermodynamic equilibrium (in a given volume with a given total energy), lead without any other assumption to Planck's radiation law. We postulate now what Planck had to deduce from his derivation of the radiation law. This postulate has been proved through innumerable experiments, so that now one is justified in taking this as a given fact in starting calculations.

The classical theory was at a deadlock, and only a genius such as Planck's could overcome the formalistic difficulties by assuming intuitively the only possible way out, the existence of discrete energy quanta of magnitude $h\nu$. Nowadays this must be considered as fundamental a law, and probably just as reliable, as the law of the conservation of energy or the law of entropy. *Whereas the number and kind of elementary particles are increasing all the time, there remains only one elementary quantum of action, Planck's* h.

The riddle of the dual nature of particle and light quantum is not solved through Bose's derivation of Planck's law; it is simply introduced as a fact. Also the questions whether the principle of causality fails in the realm of quantum theory, and whether Heisenberg's uncertainty relation, which follows logically if one uses Newtonian point mechanics, is the last word of wisdom, are not even touched. Planck himself considered the complete clarification of these questions as a goal still to be reached. Thus in the last sentence of an essay in *Naturwissenschaften* (1943) he says, "I am furthermore convinced that we will need still more profound, at the present time not even clearly predictable, changes in our physical concepts before the quantum theory will have the degree of perfection that used to be ascribed to the classical theory."

We must remember that Planck actively supported Einstein's special theory of relativity. In a detailed paper in the *Annalen,* he gave the relativistic treatment of the dynamics of moving systems. It was Planck and Nernst who were responsible for Einstein's call to Berlin. I know from personal experience that Planck was at first skeptical about the general theory of relativity, but was unable to resist the great ideas of this theory very long.

What we have said so far, in considering the scientific development and the investigations of Planck, reveals many characteristic traits of his personality: his entirely independent way of thinking, his tremendous superiority to most of his contemporaries, and his happy disposition, which was not deterred by the lack of appreciation he at first encountered. But to get a better picture of his personality we should go into some details of his personal life and into the manifold activities that are not immediately connected with his scientific work.

Because of his great musical ability, Planck as a student came in contact with many art circles in Munich. He was frequently with the families of Paul Heyse, Piloty, Woelfflin, Stieler, etc. He participated in theatricals and he wrote songs, short plays, and even an operetta. Planck had the gift of absolute pitch. In school he sang the soprano parts of the great oratorios in boys' choirs. As a student, he was second choirmaster in the academic singing society, and he played the organ at church. He systematically studied piano during his student years in Berlin, so that throughout his whole life he found a daily joy and relaxation in playing the piano. Returning to Munich, he studied harmony and counterpoint with Rheinberger. He particularly liked to play Schubert and Brahms.

Planck's call to Kiel meant not only scientific success but also personal happiness. While living with his parents, he had the most charming and comfortable life imaginable, but the desire to be independent became more and more pressing, and he was eager to have a home of his own. In 1887, at the age of not quite twenty-nine years, he married a friend of his youth, a daughter of the Munich banker Merck, Marie Merck, with whom he had two sons and two daughters. She died in 1909.

In Berlin, he first lived in the west end, but later he built a villa in the Gruenewald. On Planck's arrival in Berlin, von Siemens and Helmholtz were the spiritual leaders of the Berlin Physical Society. Planck during his Berlin student days did not appreciate Helmholtz' lectures, and Helmholtz in turn ignored Planck's Ph.D. thesis; however, as a colleague of Helmholtz, Planck soon became his great admirer. "In his personality," so Planck wrote later, "was embodied the dignity and truthfulness of his science." Every appreciative or commendatory word of Helmholtz gave Planck more satisfaction than any outside success. Throughout his whole life he treasured the appreciative words of Helmholtz after his memorial address on Heinrich Hertz in 1894. Planck participated many times in the social gatherings of the Helmholtz family, and he wrote of how memorable were the evenings spent at the Helmholtz' hearing Joseph Joachim play his own arrangements of the newly published Hungarian dances by Brahms, or Marianne Brand and the baritone Oberhauser singing "Wotan's Farewell" from *Die Walküre.*

After Helmholtz' death, Planck continued the musical tradition in his own home in the Gruenewald colony. He played an hour every day and also conducted a choir of friends and students. When three of his fingers became stiff, he still spent some time every day at the piano and, as a physicist, derived particular pleasure from the harmonium with natural scale, a complicated instrument because of the large number of keys.

Music was not Planck's only source of recreation and relaxation. Every year, he spent several weeks in the mountains, where he undertook regular climbing tours. Even now, his name may be found in the registers on many mountaintops. At the age of seventy-two he climbed the Jungfrau, and at seventy-nine the Grossvenediger. At home he went regularly for walks. Since he himself had such a strong need for exercise, he very energetically recommended exercise for the students during the time when he was Rector at the University of Berlin (1913–14). In every respect, Planck's life was arranged in such a way that he never overworked; he was able, therefore, to make the most of his tremendous talent. For him, as only rarely for anyone else, the old saying is true: *In corpore sana mens sana.*

In order to devote the necessary amount of work to his research in physics, in spite of leading a carefully regulated life, wise limitations were necessary. This explains why Planck never had a large institute with many assistants and doctoral candidates. After holding his lectures and his recitations, he usually went home. Thus one may understand why Planck had only nine doctoral students altogether. As he had finished his own thesis entirely unassisted, he also expected from each Ph.D. candidate a large amount of self-reliance. As an example, Planck merely gave me the theme for my own dissertation without ever asking how the work was progressing; and when I delivered it after half a year, Planck accepted it without changing a single word and had it published. Those who took degrees with him were: M. Abraham (1897), M. v. Laue (1903), M. Schlick (1904), Von Mosengail (who shortly after his examination had a fatal accident in the Alps), and I myself (1906), Reiche (1907), Lamla and W. Schottky (1912), and W. Bothe (1914). The student who was closest to him, according to his own words, was Laue.

Obviously, not only his few doctoral candidates, but also the many who took his lectures and learned from his books must be considered as Planck's students. Altenkirch, a specialist in technical thermodynamics (recently a Linde medalist) is one of them. Planck's lectures, all of which I attended, were prepared to the smallest detail, and were of unsurpassed clarity. To hear them was an aesthetic pleasure. Of all the lectures I have ever heard, Planck's have made the deepest impression. As vivid as if it had been yesterday is the set of lectures given during the winter semester of 1905–06, when he lectured for the first time on the quantum theory and discussed the elementary quantum of action. It was almost as if he were embarrassed to talk about his own ideas, which it was absolutely necessary to discuss with his own students. In his lectures and recitations his students were introduced to theoretical physics, and they learned to discuss all questions in a thorough, logically indisputable manner.

One activity in which Planck participated regularly and actively was the physics colloquium at the University of Berlin. It was an especially outstanding period when Nernst, Einstein, Laue, and, for a time, Schroedinger were in Berlin. The characteristic differences in their various points of view became particularly clear. Planck was always very cautious in his remarks. Laue was the very soul of the colloquia, and Einstein and Nernst had something to say on every subject, with an amazing presence of mind and without long deliberation. We had especially lively times when Ehrenfest, with his effervescent temperament, was a guest in the colloquium. Planck, however, always maintained his poise and dignity. In the thirties he was the great silent one in the colloquium. He attended the meetings faithfully without ever taking part in the discussion. This self-restraint was characteristic of his type of mind. He must have had the feeling that he no longer had enough presence of mind to discuss questions spontaneously, despite the fact that, up to his last year, he was able to think as logically and sharply as anyone else if he had the time and leisure to do so.

Planck's dignity and graciousness manifested themselves in the administration of the various positions he held at different times in Berlin. From 1912 to 1938 he was permanent secretary of the mathematical–physics section of the Prussian Academy of Science. His many addresses and responses to the addresses of others were characteristic of his personality. In his own inaugural address he stressed the need to turn away from the idea that all physical phenomena can be reduced to mechanical processes, the fundamental significance of the two laws of thermodynamics, the summary of experimental results through theoretical physics, which is necessary to stimulate further experiment.

In his response to Einstein's inaugural address he did not refrain from being critical. "Even if you are not satisfied with the principle of relativity in its first special form because it favors uniform motion, one should recognize this as a particular advance in knowledge; because the laws of nature which we are looking for are a special selection from the manifold possibilities of all possible relations."

Later, however, he was not able to deny the great importance of the general theory of relativity. In response to Laue's inaugural Planck discussed qualities of leadership for a position such as Laue already held: "Conscientiousness in the pursuit of important things, patience, and the courage to stand up for his own convictions against anybody, even against his own former and different opinion." In a similar way every address he gave in the academy was always illuminated by his profound and mature personality.

With this same thoroughness and from the same point of view as he fulfilled his duties as permanent secretary in the academy, Planck also took the position of president of the Kaiser Wilhelm Society (1920–37) in difficult times, when national socialism displayed its corrupt power. The greatest disappointment in this position was perhaps his interview with Hitler in an attempt to retain the Jewish associates of the Kaiser Wilhelm Institute. The interview had no practical results, and this may have been the reason for the disastrous end of his favorite son. His presidential post, however, gave Planck the opportunity to venture beyond his special professional duties—a welcome opportunity for his broad interests, which also encompassed philosophical and religious problems.

This attitude is shown in all Planck's scientific work. He himself says in his essays in *Naturwissenschaften* (1943), "Of primary interest to me in physics were all the great general laws, which are significant for all processes in nature independent of the properties of the bodies involved in the process, and independent of the idea which one has about their structure. For this reason the two laws of thermodynamics are of particular interest for me." How far his interest went beyond physics is easily seen by looking at his lectures and essays in his later years. They deal with the idea of causality in physics, with determinism and indeterminism, with the meaning and limits of exact science, with religion and science, with phantom problems about which he lectured in Goettingen in 1946. Let us quote from the essay on the meaning and limits of exact science just one sentence, which is particularly characteristic of Plank's thinking: "The only thing which we can claim with certainty as our property, the greatest good which no power in the world can rob us of, and which can make us happy forever as nothing else can, is a pure spirit, which finds its expression in the conscientious fulfilling of one's duties." Even if Planck's collection of philosophical writings—e.g., his lecture on phantom problems—did not find general approval, in all of them we see the burning wish to obtain honest clarity about the most profound problems of human life.

The greatness and strength of his character Planck showed particularly in the way he carried his personal burdens: The four children by his first wife all died. His twin daughters both died in childbirth. The oldest son was killed in the first world war near Thiaumont in France. The second son came to a frightful end in January 1943 as a victim of Nazism. When Planck heard of it, he wrote to Sommerfeld that he had lost his closest and best friend. He was wrestling for the power to give his future life meaning by conscientious work.

In his personal misfortunes he was comforted by his second wife (nee Hoesslin), the niece of his first wife, whom he married one year after the latter's death. The second world war destroyed Planck's beloved home in the Gruenewald, with all his possessions, including his carefully kept diary. He and his wife were forced to flee to his estate of Rogaetz on the Elbe. He almost died in an air raid on Kassel. From Rogaetz the Americans took him to Goettingen, were he found refuge with some kinfolk and where he spent his last two and a half years. He died in the hospital on October 4, 1947, about half a year before he would have celebrated his ninetieth birthday.

Planck's second wife, Marga, was up to the last hour a self-sacrificing help to him. On all his mountain trips she was a faithful companion, and in his home and in his life she provided all the graciousness that he desired. Without her his life would have been extremely difficult. She survived him by one year.

Many honors came to Planck in the course of his life, and they may have compensated for the fact that in the beginning he found no recognition at all. He was a member of all German and of many foreign academies. As a member of the Royal Society of London, he participated in the Newtonian celebration held in London the year before his death. A great many scientific societies made him an honorary member. He was many times an honorary docter (e.g., Cambridge). He also was awarded the Lorentz medal, the Order Pour le Merite (*Friedensklasse*), of which later he became Chancellor; and perhaps the greatest recognition, the Nobel prize for his radiation law (1919). Besides his trip to London in 1946, Planck accepted many invitations to foreign countries (America, France, England, and Switzerland). He was a regular participant in the Solvay Congresses in Belgium.

His sixtieth birthday was celebrated by the German Physical Society in Berlin. Addresses were given by Warburg, Laue, Sommerfeld, and Einstein. His seventieth birthday was celebrated in his home and by the Physical Society of Berlin. Particularly imposing was the celebration of his eightieth birthday in the Harnack-Haus in Berlin, in which Ramsauer, Grueneisen, Debye, Laue, and the French Ambassador, François Poncet, gave addresses. The beautiful gold medal Planck awarded to L. de Broglie was accepted for him by the French Ambassador. On the evening of Planck's eightieth birthday there were addresses by Sommerfeld, by Fokker for the Dutch physicists, and by Kopff for the astronomers. Planck found simple dignified words of thanks on these occasions.

Planck will go down in history as one of the immortals, the man who had the courage to break with classical physics and to introduce the elementary quantum of action. In the hearts of all who were close to him he will remain to their own last hour a pure, simple, and noble character whom they recall with deep veneration and love.